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NSAC Whitepaper on Applications and Nuclear Data

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Contents

Applications and Nuclear Data

The impact of the research described in this session is ubiquitous, solves a wide range of “real world” problems, and dramatically improves people’s lives. This research is diverse and hard to cover completely in a short section. Applied nuclear physics research is important for national security, medicine, nuclear energy, industry, materials, and education and the nuclear data derived from such research needs to be accurate, reliable and accessible to many different research communities.

Applications

National Security

The Stockpile Stewardship Program (SSP) is responsible for ensuring the safety and reliability of the nation’s nuclear weapons without resorting to testing. This requires improving the quality and availability of nuclear data used for interpretation of nuclear events. This is accomplished with a combination of robust experimental efforts at current and future facilities, such as FRIB, and theory. Isotopes of interest span a range of half-lives which means a combination of experimental techniques will be required to make new measurements. Nuclear data improvements needed include better measurements of half-lives, decay branching ratios, reaction cross-sections, level density and gamma-ray strength functions. Two examples illustrate some of the needs: 1) any measurements on reaction cross-sections induced on short-lived fission products which require in-beam experiments, and 2) measurements on reaction cross-sections of radioactive nuclei for which isotope harvesting is beneficial.

Improved knowledge of production and destruction reactions for A=95 fission products is desired. The cross-sections of interest within the region are shown in Fig. 1, with ^{95}Sr being perhaps the most important nuclide to obtain experimentally determined cross-sections. Generation of ^{95}Sr beams at CARIBU or FRIB, coupled with developments of inverse kinematics reactions such as (d,p) reactions, will enable experimental determination of a few key cross-sections and improve the theoretical models used to calculate the other reactions and cross-sections. Experimental data for several other mass regions, A=144 and A=147, is desired.

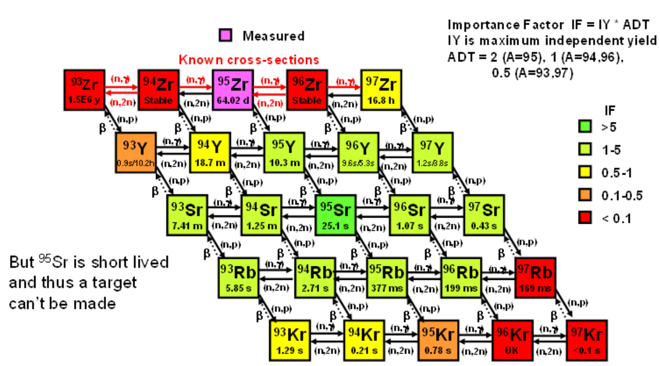

Figure 1: Part of the chart of nuclides showing the neutron rich fission products of interest to the SSP.

Isotopes such as ^{48}V and ^{88}Zr are suitable for isotope harvesting and construction of targets for conventional neutron induced experiments. In many such cases, experimental cross-section information is completely lacking, such as for $^{88}Zr(n,\gamma)^{89}Zr$. This effort is synergistic with the medical community's development of ^{89}Zr as a medical imaging diagnostic isotope. Isotope harvesting schemes to obtain ^{67}Cu from the FRIB beam dump water have shown significant promise—additional chemistry to purify Zr isotopes is under development.

Improved knowledge of cross-sections is also important in the field of inertial confinement fusion both to diagnose the performance of the experiments and to investigate the influence of high energy density plasmas on nuclear data such as reaction cross-sections at elevated temperatures and isomeric state populations. Examples include improved measurements of the $T(D,\gamma)/T(D,n)$ branching ratio for interpretation of the gamma reaction history diagnostic used at the National Ignition Facility (NIF) and other laser facilities. In addition, threshold nuclear reactions such as $^{12}C(n,2n)^{11}C$ or $^{169}Tm(n,3n)^{167}Tm$ can be used to diagnose high energy ($E_n > 14$ MeV) neutrons produced during ICF implosions. Finally, radiochemical diagnostics (charged particle and neutron induced reactions) can be used to determine if mix of unwanted material into the fusion fuel occurs and to what extent such mix affects the capsule performance.

Medical Research

Nuclear medicine uses radioactive material for safe and cost-effective imaging and treatment of illnesses. Modern technologies allow radioisotopes to be delivered directly to their targets – diseased cells. They emit radiation that allows specialists to image the extent of a disease process in the body, based on cellular function and physiology, allowing doctors a better understanding of the diseased tissue than other diagnostic procedures, which may only capture structural information. New radiopharmaceuticals for these imaging techniques can be developed to help determine which patients may respond to which treatment, paving the way for personalized medicine. Radionuclides are generally used to 'label' a radiopharmaceutical. The overall chemical structure of the radiopharmaceutical determines its biological properties, while the radionuclide determines the imaging or therapeutic properties. Investments in research and training for nuclear physics and chemistry can impact this important field in a variety of ways ranging from development of accelerator targetry to produce novel radioisotopes, to the development of new detectors for imaging techniques.

There are three major types of nuclear medicine imaging approaches: planar scintigraphy; single photon emission computed tomography (SPECT); and positron emission tomography (PET). Due to its high sensitivity and resolution, PET is fast growing as an imaging technology. The widespread use of this technology is based on the creation of specific imaging probes. For example, $[^{18}F]$Fluorodeoxyglucose ($[^{18}F]$FDG) is an FDA approved drug used for imaging in many types of cancer for staging and assessment of response to therapy. Research in the PET imaging agent development area has been typically focused on 4 main radioisotopes (carbon-11, nitrogen-13, oxygen-15 and fluorine-18). However, their short half-lives restrict radiopharmaceutical development for those that examine fast biological processes. Research into new isotopes has, therefore, gathered much momentum in recent years.

The new isotopes allow for the innovative design and integration of a broader range of PET tracers to investigate biological activity and processes. Several targeting pharmaceutical agents slowly congregate at the site of a tumor, meaning longer-lived isotopes are often chosen to optimise the accumulation of target tissue, as well as abate the background uptake. More recent studies have focused on the PET radiometals: copper-64 (^{64}Cu), yttrium-86 (^{86}Y) and zirconium-89 (^{89}Zr) with promising results. The employment of these non-traditional radionuclides is restricted by their availability as they are only produced at a few sites.

Additionally, new agents are being used for targeted radiotherapy. Recently, the FDA approval of ^{223}Ra for treatment of metastatic prostate cancer has sparked a resurgence of interest in the development of targeted radiotherapeutics. Alpha emitting isotopes such as ^{225}Ac and ^{211}At are promising for radiolabeling of the next generation of these compounds which deliver focused radiation at the diseased site, thus sparing normal tissues. Research and infrastructure to enable the widespread availability of these isotopes is vital for the clinical translation of these agents.

The development of new isotopes is a vital component of molecular imaging and therapeutic probe development. Chemical flexibility, coupled with a variety of half-lives, drive innovative development of novel agents, allowing the imaging of numerous biological processes. These studies are proving effective in the area of imaging and therapy of multiple disease processes.

Nuclear Energy

The β-decay properties of fission products have an impact on a variety of applications of nuclear science involving fission such as nuclear energy production, nuclear safeguards, and stockpile stewardship. Although hundreds of radioactive isotopes are produced in fission, often detailed nuclear data on the β -decay properties of only a handful of key isotopes is needed. With high-quality fission-product beams now available at many radioactive beam facilities around the world, detailed studies of β decay can be performed to improve the nuclear data. Below, the desired β -decay properties (β -particle energy distributions, β -delayed γ-ray branching ratios, and β -delayed neutron yields and energy spectra) are described and certain key isotopes are identified.

Beta spectral shapes

Nuclear reactors provide the highest intensity source of "man-made" antineutrinos, which are emitted in the β decay of all the neutron-rich fission products. As a result, these antineutrinos ($\bar{\upsilon}_e$s) are of great interest for fundamental neutrino physics, nonproliferation monitoring, and reactor physics. The need to precisely understand the $\bar{\upsilon}_e$ spectra emitted from the products of fissioning systems is underscored by the first measurements of θ_{13} which suggested that there may be a reactor antineutrino anomaly caused by sterile neutrinos.

Much effort has focused recently on the reactor antineutrino anomaly where the measured $\bar{\upsilon}_e$ flux is in disagreement with what has been inferred from calculations of the $\bar{\upsilon}_e$ spectra, which combine information from nuclear databases with measured total electron spectra from the major actinides. Combining data on 18 short-baseline reactor antineutrino experiments yields a ratio of observed to predicted event rate of 0.943 ± 0.023, a 2.5-σ difference from unity. However, the use of this neutrino signal for applications and for fundamental neutrino physics is greatly strengthened by a sound basis of the underlying β -decay spectra from fission fragments.

The $\bar{\upsilon}_e$ spectrum can be calculated by summing the individual β-spectra for each fission fragment weighted by its cumulative fission yield. Although there are hundreds of radioactive isotopes produced in fission, only a handful of nuclei have significant influence on the spectrum. For example, the nuclei ^{92}Rb and ^{96}Y are the are the first and second largest contributors to the neutrino spectrum, each making up 6% at 4 MeV and 21% (^{92}Rb) and 15% (^{96}Y) at 5.5 MeV of the total $\bar{\upsilon}_e$ spectrum. Given the significance of the β energy spectra of a handful of key fission products to the $\bar{\upsilon}_e$ spectrum calculations, these isotopes should be studied using β -spectroscopy and discrete β -ray spectroscopy.

Beta-delayed γ-ray branching ratios

The fission products ^{147}Nd, ^{144}Ce, ^{156}Eu, and certain other long-lived isotopes play a crucial role in science-based stockpile stewardship because determining the yield of these isotopes is one of the most straightforward and reliable ways to determine the number of fissions that occurred in a nuclear weapon test. The yield of these fission products is most precisely determined by detecting the characteristic γ-rays emitted during the β decay of these long-lived fission products. These γ rays are emitted in only a fraction of the decays, and this fraction (the γ-ray branching ratio) must be known accurately to determine the total number of fissions. However, large nuclear-decay uncertainties are currently limiting the usefulness of the existing data. The absolute γ -ray branching ratios for ^{147}Nd, ^{156}Eu, and ^{144}Ce are desired to higher precision for stockpile-stewardship applications and to greatly improve the precision and reliability with which the number of fissions can be determined.

In addition, fission-product yields are typically determined using γ -ray spectroscopy and in these cases the γ -ray branching ratios are often the largest source of uncertainty in the determination of fission-product yields. For example, recent measurements at the Triangle Universities Nuclear Laboratory (TUNL) exploring the neutron-energy dependence of fission product yields would benefit from an improved absolute normalization that could be provided by branching ratio measurements. Improved fission-product distributions would also benefit a variety of applications such as nuclear reactor design and γ -ray based safeguard applications as well as to guide fundamental theories of fission.

The central challenge in measuring these γ -ray branching ratios is to determine the total number of decays of the nucleus of interest. Properly accounting for sample limitations (impurities, self-attenuation, etc.) and any accompanying conversion electron emission play an essential role in determining the overall normalization for the decay. These challenges can be largely circumvented by producing ultra-thin samples nearly free of radioactive contaminants at the CARIBU Facility at Argonne National Laboratory and measuring the absolute number of decays utilizing a 4π β spectrometer, which can be essentially 100% efficient for a well-designed instrument, in conjunction with precision γ -ray spectroscopy.

Beta-delayed neutron emission

The neutrons emitted following the β decay of fission products (known as delayed neutrons because they are emitted after fission on a timescale of the β -decay half-lives) play a crucial role in reactor performance and control. Reviews of delayed-neutron properties highlight the need to obtain high-quality data for a wide variety of delayed-neutron emitters to better understand the time-dependence and energy spectrum of the neutrons as these properties are essential for a detailed understanding of reactor kinetics needed for reactor safety and to understand the behavior of these reactors under various accident and component-failure scenarios. For fast breeder reactors, criticality calculations require accurate delayed-neutron energy spectra and approximations that are acceptable for light-water reactors such as assuming the delayed-neutron and fission-neutron energy spectra are identical are not acceptable and improved β -delayed neutron data is needed for safety and accident analyses for these reactors. With improved nuclear data, the delayed-neutrons flux and energy spectrum could be calculated from the contributions from individual isotopes and therefore could be accurately modeled for any fuel-cycle concept, actinide mix, or irradiation history.

However, spectroscopy of 0.1- to 10-MeV neutrons is challenging and the quality of the data available today for individual nuclei is limited – in some cases discrepancies as large as factors of 2-4 in recent measurements of β -delayed neutron branching ratios have been uncovered and for the vast majority of neutron emitters, the energy spectrum has not been measured. Due to the challenges and limitations associated with existing techniques, a new approach to performing β - delayed neutron spectroscopy would be valuable for collecting the high-quality, reliable data needed for applications.

Ion traps can have as large an impact on the study of β -delayed neutron emission as they have had in the field of mass spectrometry. Trapped radioactive ions suspended in vacuum allow a new way to measure delayed-neutron properties by inferring the neutron energy from the large momentum kick it imparts. When a radioactive ion decays in the trap, the recoil-daughter nucleus emerges from the ~1-mm^3 trap volume without scattering and the recoil energy can be measured. The energy of the emitted neutron can be easily and precisely reconstructed from this recoil by conservation of energy/momentum. Because of the massiveness of the neutron relative to the emitted leptons, the recoil energy is dominated by the neutron recoil. This ability to measure the nuclear recoil unperturbed enables a novel way to perform delayed-neutron spectroscopy with high efficiency, few backgrounds, and improved energy resolution. All the well-known challenges associated with detecting neutrons are avoided. The delayed-neutron branching ratios and neutron energies can be precisely determined by detecting the recoil ions in coincidence with the β particles.

The first-ever demonstration that β -delayed neutron measurements could be made by studying the nuclear recoil was recently performed using the Beta-decay Paul Trap instrumented with β, γ -ray and recoil-ion detectors (see Fig. 2). The β -decay properties of ^{137}I were studied and the measured neutron branching ratio and energy spectrum were consistent with previous direct measurements, paving the way for future studies of beta-delayed neutron emission.

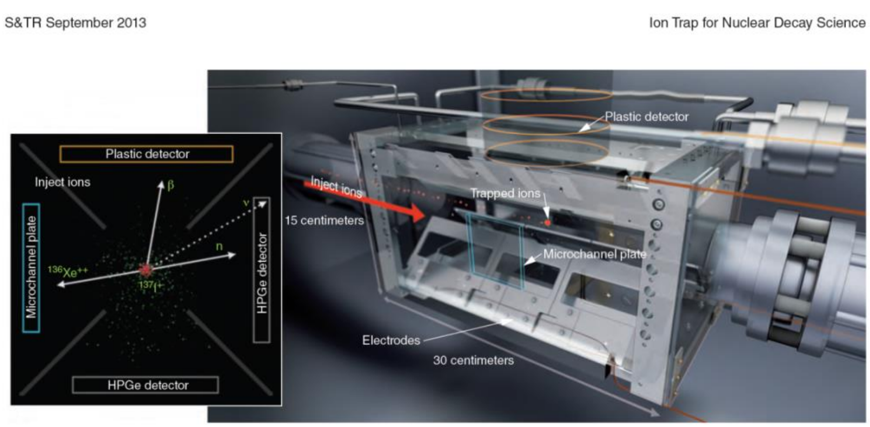

Figure 2: An illustration of the Beta-decay Paul Trap and the recoil-ion approach to β-delayed neutron spectroscopy. The box on the left shows a cross-sectional view of the ion cloud, electrode, and detector array geometry. Neutron emission is inferred from the time-of-flight of the recoil ion detected in coincidence with the emitted β particle. The graphic is from the September 2013 issue of LLNL's Science and Technology Review magazine.

Industry and Materials

Nuclear physics applications in industry and materials encompass a wide variety of uses from non-destructive assay and analysis of manufactured items, accelerated wear testing of critical components in moving assemblies, determination of flow pathways and dynamics in complex systems including the environment, and protection of electronic components from single event upsets due to cosmic rays. Many of these applications rely on nuclear physics expertise and/or experimental capabilities.

> A recent avionics incident highlights the single event effect problem in electronics equipment affecting people's lives. On October 7, 2008 , Quantas 72 was enroute from Singapore to Perth, Australia. Excerpts from the investigation report ATSB Transport Safety Report Aviation Occurrence Investigation AO-2008-70 indicate the seriousness of the issue. "While at 37,000 ft, one of the aircraft's three Air Data Inertial Reference Units (ADIRU) started outputting intermittent, incorrect values…Two minutes later …the aircraft flight control primary computers commanded the aircraft to pitch down. … At least 110 of the 303 passengers and nine of the 12 crew members were injured: 12 of the occupants were seriously injured and another 39 received hospital medical treatment."
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> The report concluded that one possible cause was: "The other potential triggering event was a single event effect (SEE) resulting from a high-energy atmospheric particle striking one of the integrated circuits within the CPU module. There was insufficient evidence available to determine if an SEE was involved, but the investigation identified SEE as an ongoing risk for airborne equipment." Testing of components in this plane had occurred with 14 MeV neutrons only, missing the large amount of more energetic neutrons present in cosmic ray induced neutrons.

Accelerated testing of electronic components occurs at several accelerator facilities, with industrial companies interested in matching cosmic ray fluxes and intensities with cocktails of charged particle beams or neutrons with the appropriate energy spectrum. One of the most concerning types of single event effects observed in electronics is due to cosmic ray induced neutrons because of the long mean-free paths of neutrons in the atmosphere and materials. This is of extreme concern to the aviation and aeronautics industry because aircraft fly at altitudes where fluxes of neutrons are over two orders of magnitude higher than at ground level. The neutrons are produced by cosmic rays in the upper atmosphere, penetrate to lower altitudes, interact with Si atoms in the computer/electronics components creating charged particles that recoil through the material, and deposit charge in sensitive volumes of the material causing the state of a node to change resulting in a variety of effects that are observable in the device like data corruption or single event latch-ups, burn-ups, or gate ruptures. Industry trends to lower voltages and smaller feature size are thought to increase the failure rate due to these kinds of events. Similar devices can have very different failure rates, however, the failure rates due to these kind of single event effects are equal to all other kinds of failures in the devices combined.

Neutron experiments can be performed at Los Alamos National Laboratory at the LANSCE facility, where the neutron spectrum from the spallation neutron source has been measured to match the cosmic ray neutron spectrum. Accelerated testing of components can occur by operating devices while they are being irradiated with neutrons and observing the single effect upset rate in either a component or whole device. Typically these irradiations occur over the course of a day or week of testing in order to develop equivalent single event rates due to cosmic ray neutrons. Cosmic ray neutrons affecting airplane computer systems [ATSB Transport Safety Report Aviation Occurrence Investigation AO-2008-70] and supercomputer calculations [IEEE Trans. Dev. Mat. Reliab. <u>5</u> 2005] have been documented.

Education

Pervasive throughout all of the presentations and the discussion mentioned in this document is the important educational development of undergraduate and graduate students involved in all areas of research discussed. The importance of the students to the research, and the accessibility of the applied research and nuclear data for student research projects and theses, is not repeated in detail here because these important relationships have been stated more eloquently in numerous other forums and whitepapers; most recently in the whitepaper from the Education and Innovation town meeting held earlier at MSU. We underscore their recommendations and conclusions and note the contributions to nuclear data and applied nuclear research made in educating students.

Nuclear Data: Accurate, Reliable and Accessible

The primary activities of the U.S. Nuclear Data Program (USNDP) are to collect, evaluate, and disseminate nuclear physics data for basic nuclear physics and applied nuclear technology research. The nuclear data infrastructure provided by the USNDP impacts governmental, educational, commercial, and medical organizations in United States, and is part of the U.S. commitment to the international nuclear data networks. Throughout this presentation various examples of nuclear data measurements carried out at ANL, LANL, LBNL and TUNL were given; these measurements have an impact on, for example, parity violation limits, astrophysics, medical isotope research, stockpile stewardship, and measurements of "enabling data" that are useful or necessary for analysis of data from other experiments. In each case, improvement in the accuracy and precision of the data can provide improvement in some associated underlying science or application. Throughout the session there was an unresolved discussion theme connected with associating the term "applications data" with basic science measurements that have a strong association with meeting the nation's nuclear data needs. In any case, it is evident that the need for convenient access to the best nuclear data is increasing, and therefore it is critically important to maintain a high level of expertise in the area of nuclear data evaluation to assure the continuation of the nuclear databases with sufficient breadth and quality to meet the requirements of advanced computational applications.

The domestic and global demand for nuclear data continues to increase, as nuclear science and technologies find new utility in our advancing society. Detailed and complex nuclear data and associated libraries are now commonplace in many applied fields, including energy, medicine and security among others. The collections of nuclear data libraries represent the collective annals of nuclear science research and discoveries. Insights to new discoveries benefit greatly from systematic analysis of prior studies, and from the ability to access these data promptly. Under these circumstances, the convenient availability of comprehensive, up-to-date, and well-ordered databases is an essential tool for the nuclear physics research community and applications specialists who need such data as part of their daily routine. Such credible and reliable libraries act as a bridge between science, technology, and society by making the results of basic nuclear physics research available to a broad audience of users, and hence, having a profound effect on the socioeconomic applications of modern nuclear science.

The basic and applied science research communities that fulfill these demands are expanding the knowledge pool, as well as improving the accuracy of the data, which can have significant impact on industrial applications. Worldwide efforts are coordinated primarily by the International Atomic

Energy Agency in Vienna (IAEA) and the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (NEA-OECD) in Paris. The development and maintenance of nuclear data libraries, and dissemination of nuclear data to various user communities is the main goal of the international networks associated with these agencies: the Nuclear Reaction Data Centres Network (NRDC/IAEA), the Nuclear Structure and Decay Data evaluators (NSDD/IAEA), and the Working Party on International Nuclear Data Evaluation Co-operation (WPEC/NEA). More information about them can be found at http://www-nds.iaea.org/nrdc.html, http://www-nds.iaea.org/nsdd, and http://www.nea.fr/html/science/wpec.

The DOE/SC-funded U.S. Nuclear Data Program (USNDP) comprises nuclear data experts from national laboratories and academia across the United States who collect, evaluate, and disseminate nuclear physics data for basic nuclear physics and applied nuclear technology research. The focal point of the network is the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory, which is the major outlet for storing and disseminating nuclear data in the U.S. The services provided by the national network of nuclear data evaluation groups are essential to organizations with missions that require access to nuclear data. The nuclear data infrastructure provided by the USNDP impacts governmental, educational, commercial, and medical organizations in United States, as illustrated in Figure 3, and is part of the U.S. commitment to the international nuclear data networks.

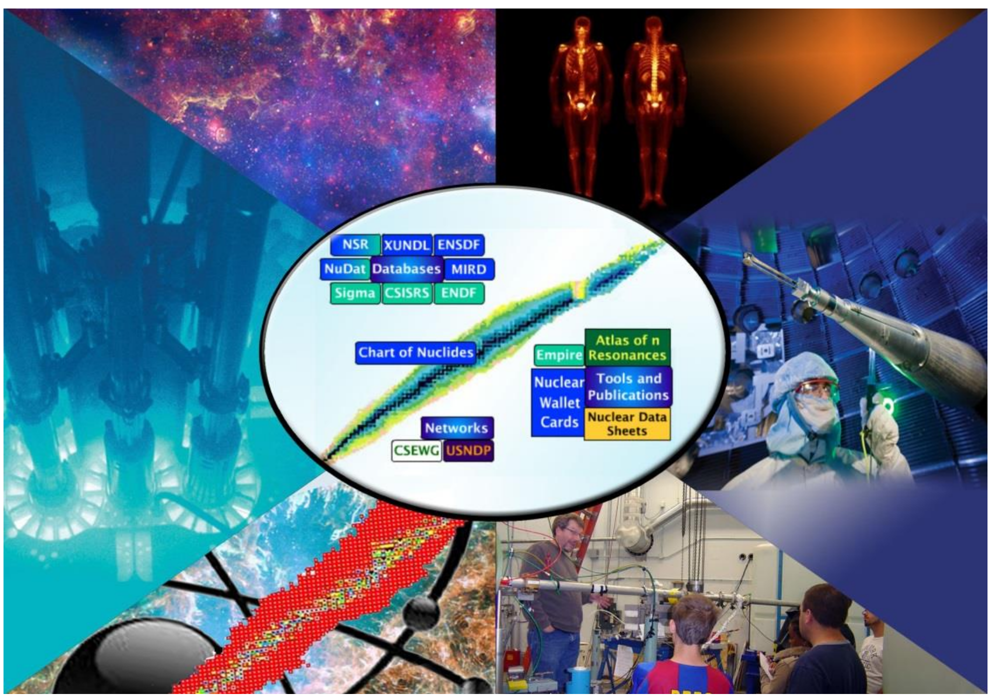

Figure 3: The core nuclear physics databases and products of the USNDP, and their main areas of impact for science and technology.

The mission of the USNDP is to provide current, accurate, authoritative data for workers in pure and applied areas of nuclear science and engineering. This is accomplished primarily through the compilation, evaluation, dissemination, and archiving of extensive nuclear datasets. The USNDP also addresses gaps in the data, through targeted experimental studies and the use of theoretical models. By carrying out this mission over the next decade, the USNDP network will continue to develop and maintain key components that motivate basic science discovery and support the progress of advanced simulation codes. The critical issue is to maintain a high level of expertise in the area of nuclear data evaluation to assure sufficient breadth and quality of the nuclear databases and to meet the requirements of a continuously developing user community.

Common Themes

Several common themes emerge from this diverse topic area. Applied research often benefits basic research (and vice versa) and a strong synergy exists between basic and applied research – there are many connections between the communities and the scientific work that are mutually beneficial. There is a diversity of funding sources and laboratories pursuing applied nuclear science, with much of the research resulting in significant contributions (PRLs, etc.) to nuclear science. Modest investment in nuclear data and technologies has large impact on nuclear science and education and opportunities exist for complementary nuclear data efforts. The economic and societal impact of this research is huge in areas of national security, medicine, nuclear energy, industry, materials, and education. Examples include: Single-Event-Upset electronics testing that benefits the airline industry – affecting 825 million passengers last year; Nuclear power industry that generates ~20% of US electricity – affecting 60 million US residents annually; ^{99m}Tc for medicine used in 20 million patient treatments last year; and NNDC nuclear data retrievals of more than 3 million last year. The impact of the research described in this section is ubiquitous, solves a wide range of "real world" problems, and improves people's lives.

Recommendations

The working group developed one recommendation for each area as indicated below:

Applications

- Because of the broad economic and societal benefits of applied nuclear physics efforts to national security, medicine, nuclear energy, industry, materials, and education, we recommend increased support for innovation and applications within DOE/SC/NP and NSF.

Nuclear Data

- Because of the critical and pervasive use of nuclear data in a variety of basic and applied scientific efforts, we recommend strong support for the US Nuclear Data Program, which includes timely compilation, evaluation, secure archiving, and dissemination of nuclear data.

We recognize the similarities between the recommendation from the Education and Innovation town meeting held earlier at MSU and these, and therefore also endorse that draft recommendation.